Wave Setup

FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report

February 2005

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Acronyms

ANWM	advanced numerical wave models
EBP	Equilibrium Beach Profile
ERDC	Engineer Research and Development Center
CEM	Coastal Engineering Manual
GROW	Global Reanalysis of Ocean Waves
NOPP	National Oceanographic Partnership Program
SPM	Shore Protection Manual
SWL	stillwater level

1 INTRODUCTION

This report provides recommendations for a program leading to improvement of the current FEMA Guidelines related to Wave Setup. Six Wave Setup topics were developed at the December 2003 Workshop. Three of these topics were labeled “Critical” and applied to all three geographic areas, two were designated “Important” and also applied to all three geographic areas, and one was designated “Available” and was later transferred to another group. Therefore, the five topics addressed by the Wave Setup Group are as follows:

Wave Setup Topics and Priorities					
Topic Number	Topic	Topic Description	Priority		
			Atlantic / Gulf Coast	Pacific Coast	Non-Open Coast
44 & 45	Define, Document, Compile Data	Better define and document, summarize what to consider and how to approach; data requirements. Compile example data/sets to perform tests	C	C	C
46	Interim Method	Develop “Interim Method”. (Look at CEM as a fall back, or Univ. of HI SPM procedure)	C	C	C
47	Develop Ideal Method - Coupled	Develop “Ideal Method” coupled with storm surge and waves to develop setup	I	I	I
48	Dynamic Wave Setup	Develop procedure for dynamic wave setup	I	I	I
Key: C = critical; A = available; I = important; H = helpful					

1.1 WAVE SETUP FOCUSED STUDY GROUP AND APPROACH

The Wave Setup Group is made up of Ian Collins, David Divoky, Darryl Hatheway, Norman Scheffner and Bob Dean who served as Team Leader for this effort.

To provide structure to our efforts and to avoid unnecessary duplication, the following approach was adopted—the Team Leader developed background material, reviewed available information, and developed draft writeups for the approaches. The draft write up was then distributed to the Team Members who contributed information of which they were uniquely aware, critiqued and contributed to the draft writeups and accomplished specific components of the overall effort leading to this report.

1.2 CURRENT FEMA GUIDANCE ON WAVE SETUP

The current FEMA guidance for Mapping Partners to calculate wave setup relies on the 1984 Shore Protection Manual (SPM) that focuses on the average (or static) wave setup. The guidance recognizes the effect of beach slope and deep water wave steepness (H_{os}/L_{os}) based on the deep water significant wave height (H_{os}) and associated length (L_{os}). Figure 1 presents current FEMA guidance (page D-66 f Guidelines and Specifications). As seen from this figure, wave setup increases with steeper beach slopes and smaller wave steepness, H_{os}/L_{os}. The guidance also briefly discusses wave setup in the presence of a reef or offshore berm, but offers no specific guidance on these settings. Figure 1 shows predicted wave setup values of 7% to 8% of the deep

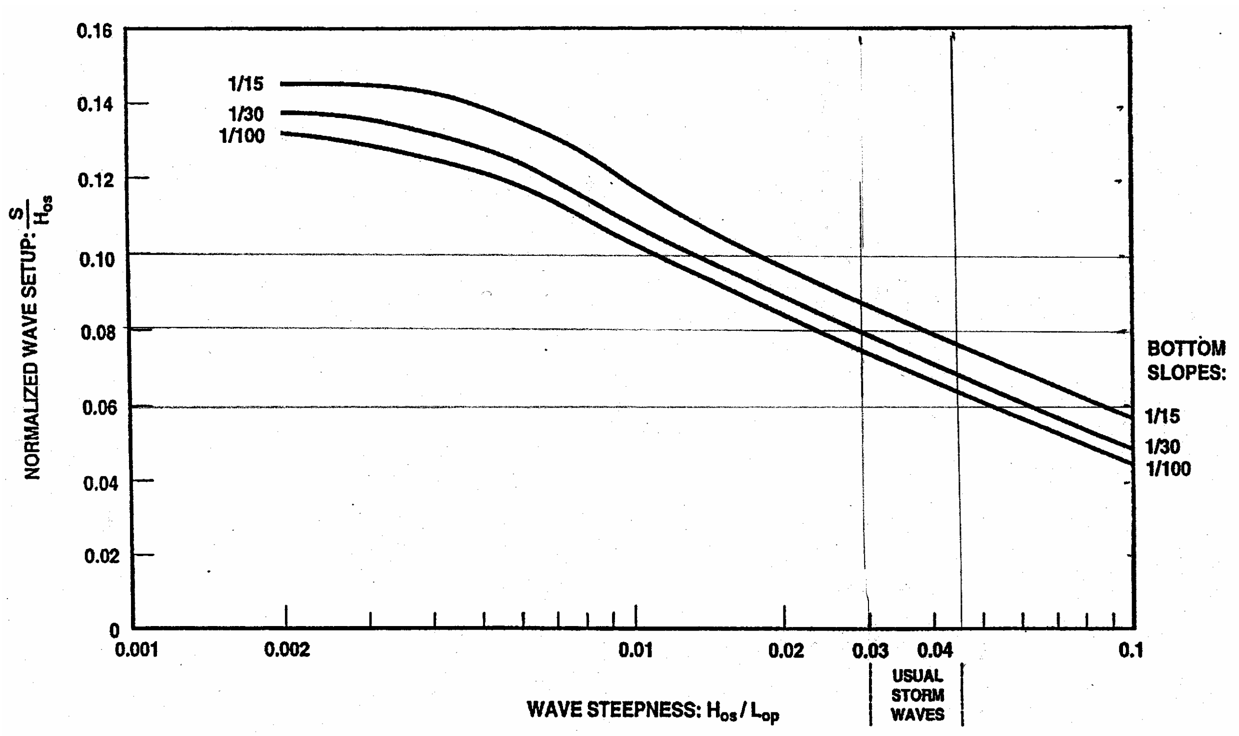


Figure 1. Current FEMA guidance on wave setup based on 1984 Shore Protection Manual.

water wave height for deep water wave steepness values of 0.03 to 0.04–typical for storm seas. Wave setup values of up to 10% are predicted for waves of lower steepness, which could govern for areas exposed to large, long period swell, such as the Pacific Coast. The recommended beach slope is the average from an offshore distance corresponding to a depth of $2H_{os}$ to the shoreline. The current guidelines do not contain any mention of dynamic wave setup, i.e., the fluctuating component of wave setup caused by groups of waves.

1.3 APPLICATIONS OF EXISTING GUIDELINES TO WAVE SETUP TOPICS

Wave setup can be a significant component of the total 100-year surge elevation on all coasts. The narrow Pacific continental shelf results in the combination of wave setup and astronomical tide being the two largest components of the 100-year surge. On the Atlantic and Gulf shorelines, wave setup can range up to 50% of the total 100-year surge in areas with narrow continental shelves.

As noted, current guidance is based on the 1984 U.S. Army Corps of Engineers (USACE) Shore Protection Manual (SPM 1984) for irregular waves on an open coast and for planar beach profiles (uniform slopes) and does not address many settings related to FEMA's responsibilities. The recent USACE Coastal Engineering Manual (CEM), which replaces the SPM, provides guidance for both regular and irregular waves. The CEM results for irregular waves are presented in graphical form and do not extend to the shoreline; however, if these results are extrapolated to the shoreline for comparison with the current guidance (SPM), the CEM wave setup values are consistently higher than the SPM values. Two common beach slopes are presented in SPM and CEM: for the 1:30 slopes, the CEM values are approximately 1.6 times (60% higher than) the SPM values and for the 1:100 slope, the CEM values are approximately a factor of 1.4 times (40% higher than) the SPM values.

Of the coastal counties where FIS studies have been conducted, approximately 40% have included wave setup in the 100-year FIS elevations. Those counties that have included wave setup in the 100-year elevations are predominantly those that were conducted in recent years and/or those that have been restudied after elevations were judged to be too low, in some cases based on high water marks or other data following major storms. For those counties where setup has been included, the methodologies employed have not been entirely consistent, but have relied predominantly on guidance provided by the USACE through various editions of the SPM. In addition to establishing a consistent procedure to be applied at the coast, the issue of wave setup variation over inland flooded areas is of concern and is not addressed in the SPM guidance. Updates of the FIRM's to include wave setup (i.e., increase flood levels) have led to expensive and counterproductive appeals. Two examples of such appeals have been in Pinellas County and Collier County, Florida, where much of the concern was focused on the incorporation of wave setup. Thus it is considered essential to establish a consistent methodology for all calculations of wave setup with as much adherence to the physics of the system as possible.

2 CRITICAL TOPICS

As noted, the December 2003 Workshop identified three "Critical Topics" on wave setup: 1) "Better define and document; summarize what to consider and how to approach; data requirements (Topic 44)"; 2) "Compile example/data sets to perform tests (Topic 45)"; and 3) "Develop interim method (look at CEM as a fall back, or University of Hawaii SPM procedure) (Topic 46)." "Critical Topics" are those that could be accomplished within six months. All three of the critical Wave Setup Topics apply to the three geographic areas defined: 1) Atlantic/Gulf Coasts, 2) Pacific Coast, and 3) Sheltered Waters.

2.1 TOPIC 44: BETTER DEFINE AND DOCUMENT; SUMMARIZE WHAT TO CONSIDER AND HOW TO APPROACH; DATA REQUIREMENTS

2.1.1 Definitions

Wave setup is the increase in mean water level above the stillwater level (defined as including the effects of all other forcing except wave setup) due to momentum transfer to the water column by waves that are breaking or otherwise dissipating their energy, see Figure 2. Wave setup is the

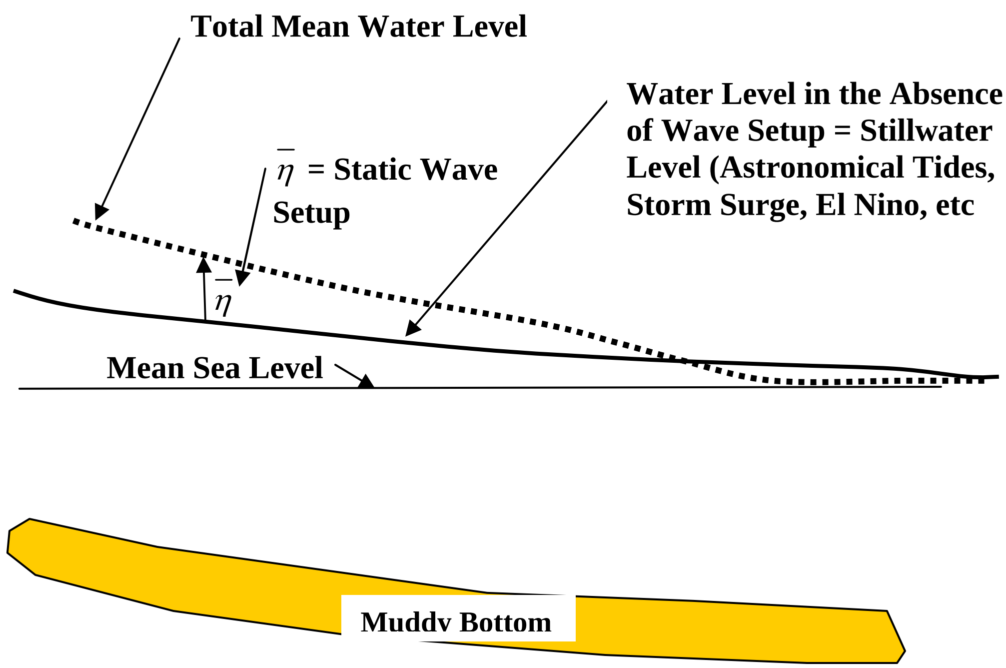


Figure 2. Definition Sketch for Wave Setup

increase in water level with periods ranging from several to tens of periods of the dominant incident wind wave period. A typical wind wave period is in the range of 8 to 15 seconds.

Wave setup is a component in wave runup in the same manner as the wind and barometric components of the storm surge are components in wave runup. In those portions of the nearshore zone where water is always present, the definition of wave setup is simpler than in the runup zone that is alternately wet and dry. In locations where water is always present, wave setup is the deviation of the mean water level from the stillwater level (SWL). The SWL is defined as the water level in the absence of waves but with all other processes present.

Wave setup includes a static component and a dynamic component with the dynamic component varying much more slowly than the dominant wave period. Figure 3 is a sketch illustrating these components.

A challenge in this and the wave runup issues will be to ensure that the effect of wave setup is not "double counted", i.e., not included twice because the wave setup is included to some degree in wave runup measurements. A useful and practical working definition distinguishing wave setup from wave runup elevations is: "Wave setup contributes to high water marks inside reasonably small buildings; however, wave runup does not." A second challenge is the development of an acceptable method to predict the inland excursion of the steady and dynamic wave setup components.

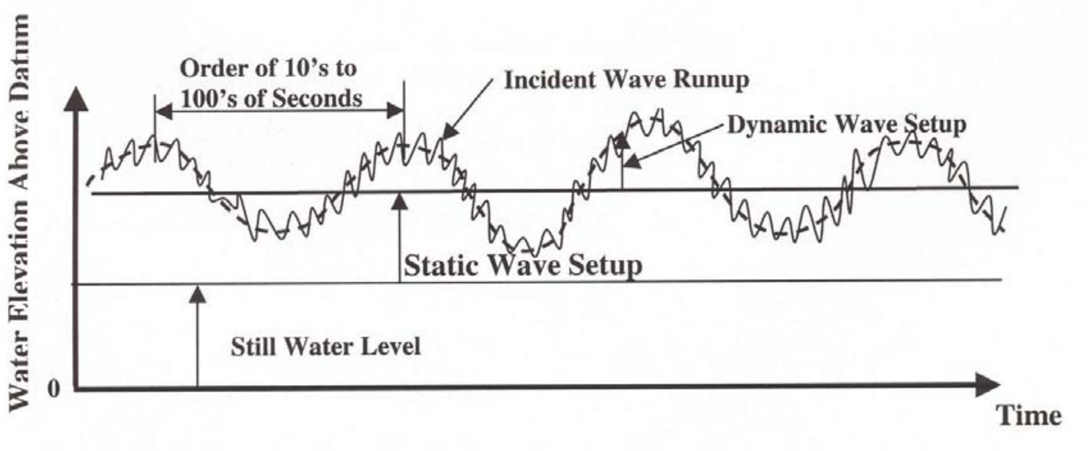


Figure 3. Definitions of static and dynamic wave setup components.

2.1.2 Physiographic Settings

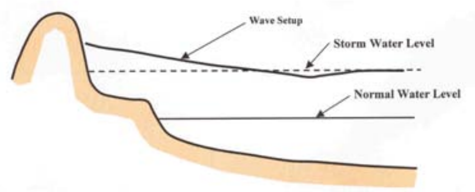
Wave setup can occur in a variety of physiographic settings that are relevant to FEMA's flooding responsibilities. Eight such settings have been identified and are shown in Figure 4. The mechanics of wave setup in some of these settings may be similar or identical; however, the range of possible settings is included here for completeness.

2.1.3 Considerations and Approaches

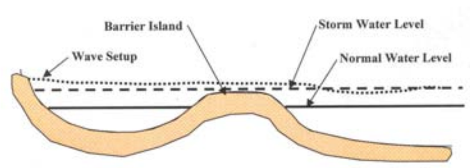
As the NFIP Program matures, it is clear that the programs and procedures employed will to be more complete and represent the physics more effectively. This is also the case for wave setup. The systems of interest are three dimensional and complex and it is believed that the next generation of models and procedures will be able to consider the physical system and forcing more completely and realistically. If this is correct, the problem of predicting realistic values of wave setup will be on a much more solid footing and should minimize future appeals based on considerations of out-of-date methodology. It is anticipated that the next generation of models will still require some empiricism and ad hoc approaches; however, artificialities will be reduced considerably relative to present methodology.

The physics of the static wave setup component are reasonably well understood and governed by the following equation

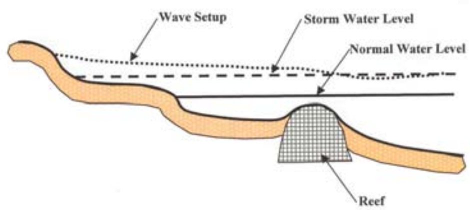
$$\frac{\partial \bar{\eta}}{\partial x} = \frac{1}{\rho g (h + \bar{\eta})} \left(-\frac{\partial S_{xx}}{\partial x} + \tau_b \right) \qquad (1)$$



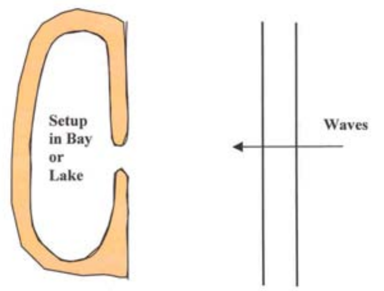
Setting 1. Long Straight Beach.



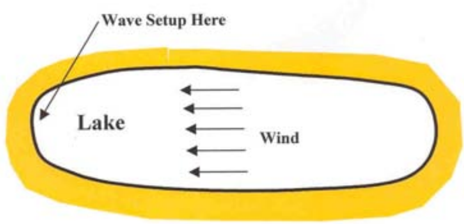
Setting 2. Flooded Barrier Island.



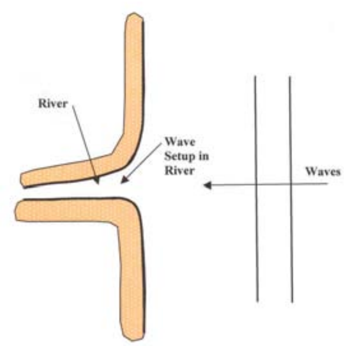
Setting 3. Fringing Reef.



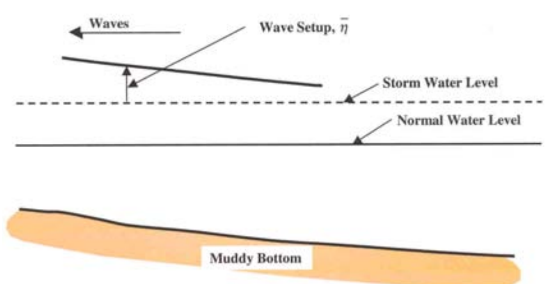
Setting 4. Wave Setup in Lake or Bay.



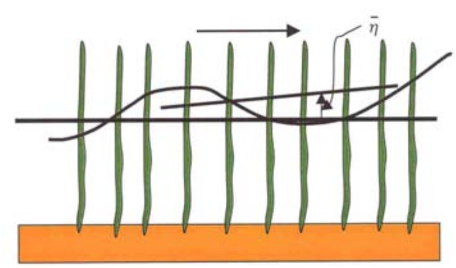
Setting 5. Wave Setup in Enclosed Water Body.



Setting 6. Wave Setup in River.



Setting 7. Wave Setup Over Muddy Bottom.



Setting 8. Wave Setup Through Vegetation.

Figure 4. Eight wave setup settings relevant to FEMA's responsibilities.

in which $\overline{\eta}$ is the steady state component of the wave setup, x is the shoreward directed axis, ρ is the mass density of water, g is gravity, h is the stillwater depth, S_{xx} is the flux of momentum in the direction of wave propagation, and τ_b is the bottom friction. The S_{xx} term is defined as

$$S_{xx} = \overline{\int_{-h}^{\eta} (p + \rho u^2) dz} \tag{2}$$

where p is wave related pressure, u is the horizontal component of the wave related water particle velocity, η is the instantaneous water surface elevation relative to the stillwater level, z is the vertical coordinate directed upward with its origin at the stillwater level, and the overbar indicates averaging over the wind wave period. The quantity S_{xx} can be calculated readily for linear waves; however, as will be demonstrated, nonlinearities must be taken into consideration and can result in significantly smaller values of S_{xx} than those based on linear wave theory for the same wave height. In the very nearshore (surf zone), the wave propagation direction will be nearly shore normal. But there may be regions where the wave direction and the normal to the bathymetry are not in line. In this case, the momentum stress tensor must be corrected for the relative angle.

The term $(h + \overline{\eta})$ in the denominator of Eq. (1) is relevant as it indicates that a rational wave setup model will require an appropriate wave breaking model and use of valid nearshore bathymetry rather than the assumption that the waves are depth limited. In summary, referring to Eq. (1), momentum transfer ($-\frac{\partial S_{xx}}{\partial x}$) in deeper water will cause less tilt of the water surface and since wave breaking (which governs $\frac{\partial S_{xx}}{\partial x}$) depends on the bathymetry, both wave breaking modeling and valid bathymetry will be required. Furthermore, the fact that the waves do not have infinite crest lengths implies that the momentum fluxes are not unidirectional. Also, spatial variations can result from multiple wave trains incident simultaneously from different directions.

2.1.4 Data Requirements

As noted above, improvements to this topic will derive primarily due to approaches that are more comprehensive and more inclusive of the relevant physics. At present, a fairly large number of laboratory experiments on wave setup have been conducted and several field experiments have been carried out for the express purpose of investigating wave setup. However, considerable questions remain in interpreting some of the results, especially the field data in which similar approaches have yielded substantially different quantitative results. It is noted here that establishment of the offshore (still) water level is quite difficult in most field experiments which may account for some of the differences since the wave setup is relative to the stillwater level. There are several cases in which wave setup has been identified in the field in what may be called “experiments of opportunity”, i.e., the setup appeared in either tide gage readings or high water marks. These are of direct interest to FEMA as they are usually associated with severe storm events.

It will be necessary to summarize and interpret the data (a partial such effort is included in the wave setup supporting documentation developed as part of this effort) and to locate and analyze other related data. Undoubtedly additional relevant data are available that have not been identified during this relatively brief effort, especially internationally. It is believed that an effort directed to glean wave setup information from existing tide gage and high water mark information would be fruitful. Also, a more thorough analysis of the existing experimental results (laboratory and field) may provide further quantified understanding of these results and clarify significant relationships, for example wave setup in the runup region.

Finally, it is possible that, after completion of the efforts above, additional laboratory and/or field efforts will be warranted. If this is the case, the details of these recommended efforts will be established.

Table 1 at the end of this report contains a summary of the key findings and recommendations for Topic 44. Table 2 at the end of this report presents estimates of times required to accomplish the various tasks in this topic.

2.2 TOPIC 45: COMPILE EXAMPLE/DATA SETS TO PERFORM TESTS

2.2.1 Compilation of Example/Data Sets

The compilation of data sets has been discussed in Critical Topic 1 under 2.1.4, Data Requirements, and will be addressed here only briefly. It appears that a sufficiently large unexplored data base on wave setup exists and could assist in shaping the next generation of wave setup models. Additionally, the capability of the new generation of wave models in addressing the dynamic wave setup component should be useful.

Table 1 at the end of this report contains a summary of the key findings and recommendations for Topic 45. Table 2 at the end of this report presents estimates of times required to accomplish the various tasks in this topic.

2.3 TOPIC 46: DEVELOP INTERIM METHOD FOR CALCULATING WAVE SETUP

2.3.1 General

The current FEMA guidelines for calculating wave setup have been discussed earlier in this document. This guidance is based on planar beaches (i.e., uniform slopes) and does not recognize the nonlinear effects that can be significant to the quantification of S_{xx} at breaking. Additionally, current guidance does not address the dynamic wave setup component that is relevant to beach erosion and other processes, especially on the Pacific Coast. The Coastal Engineering Manual (CEM) treatment of wave setup has been reviewed and compared with the current guidance and it is recommended that the current guidance be retained until an alternate interim method is developed.

It is recommended that an interim methodology account for the following: 1) Steady and dynamic wave setup components, 2) Irregular waves (implicit in (1) above), 3) Characterization of nearshore bathymetry, 4) A valid wave breaking model, 5) Nonlinearities in S_{xx}, and 6) Wave damping seaward of the breaking zone where appropriate. Our assessment is that the required information is available to accomplish these objectives within the time frame of six months for the most common physiographic settings of concern (Figure 4). It is anticipated that the interim methodology will be applicable to two-dimensional situations and will apply reasonably well to Settings 1, 2, 3, 5, and 8. Because of the different causes of flooding and wave setup on the Pacific Coast and Sheltered Waters (P&SW), and the Gulf and Atlantic (G&A) Coasts, the interim methods will likely be different and are presented separately in the following sections. The common elements of the two interim methods occur landward of the breaking locations. Thus, the following sections present likely procedures for the Pacific Coast and Sheltered Waters and Gulf and Atlantic Coasts separately followed by a discussion of the common elements.

2.3.2 Possible Interim Methodologies

Seaward of Breaking Region

Possible Interim Method for the Pacific Coast and Sheltered Waters

The deliberations of FEMA Workshop 2 (February 2004) established that the wave input to the Pacific Coast flooding studies will likely be the Global Reanalysis of Ocean Waves (GROW) data available from Oceanweather, Inc. These data are available commercially and represent the results of reanalysis of wind fields and wave prediction and are available at a spacing of approximately 40 nautical miles along the Pacific Coast. The information contained in these data sets is assumed to include directional wave spectra. In application to the computation of coastal flooding, these spectra and the astronomical tides are expected to serve as the primary input to the calculations.

For wave setup and wave runup, the GROW wave characteristics may be transformed to the breaking zone accounting for refraction, shoaling, and energy dissipation caused by bottom friction. This will be accomplished by the Wave Transformation Study (Topics 7–10) efforts and will not be discussed further here. As noted previously, within the breaking zone, a wave breaking model will be used to establish the wave height characteristics and to provide the basis for integration of the wave setup equation. The procedures within the surf zone are common to all coastlines and will be discussed separately.

Wave Prediction and A Possible Interim Method for the Gulf and Atlantic Coasts

It is unlikely that an interim methodology will include a combination of a storm surge model and a wave calculation capability. However, all storm surge models include a wind field model. It is envisioned that the available winds could provide reasonable estimates of waves. The method would require testing to ensure its reasonableness for wave setup purposes. A potential method is described below and outlined in the flow chart in Figure 5.

As noted, all storm surge models include a wind model for forcing; however, none of which we are aware include direct wave calculations, although efforts are underway to accomplish this objective. Since wave setup requires waves as input, a parameterization of a hurricane wave field originally developed by Bretschneider (1972) can be applied. This relationship is illustrated in Figure 6.

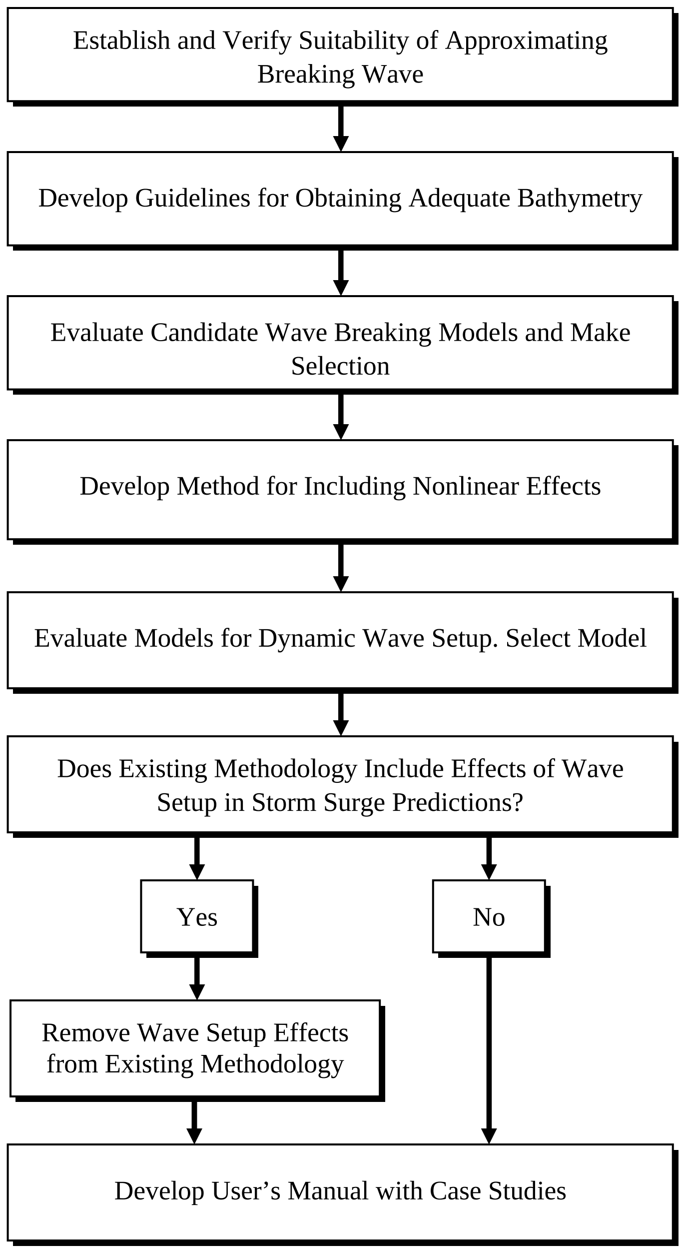


Figure 5. Flow chart for development of interim wave setup methodology.

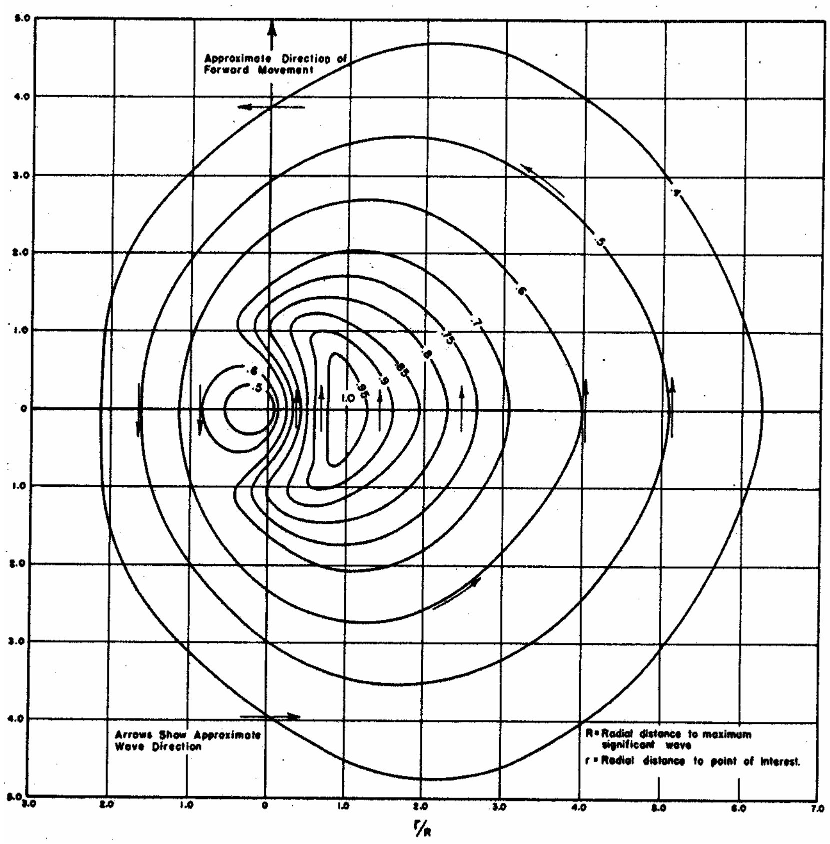


Figure 6. Non-dimensional wave height field (from Bretschneider, 1972)

The significant wave height and associated period at the location of maximum winds are described by

$$H_o = 16.5 e^{\frac{R\Delta p}{100}} \left[1 + \frac{0.208 \alpha V_F}{\sqrt{U_R}} \right] \tag{3}$$

and

$$T_s = 8.6 e^{\frac{R\Delta p}{200}} \left[1 + \frac{0.104 \alpha V_F}{\sqrt{U_R}} \right] \tag{4}$$

where the units of H_o and T_s are feet and seconds, respectively; and R is the radius to maximum winds in nautical miles, Δp is the central pressure deficit in inches of mercury, V_F is the forward translational speed of the hurricane in knots, U_R is the maximum sustained wind speed in knots, calculated at 30 feet above the mean sea surface at radius R, where

$$U_R = 0.865 U_{\max} + 0.5 V_F \tag{5}$$

and U_{max} is the maximum gradient wind speed in knots at 30 feet above the water surface. Finally, the parameter α is a coefficient that depends on the forward speed of the hurricane. For slowly moving hurricanes, the suggested value of α is 1.0. In Figure 5, the horizontal and vertical axes are non-dimensionalized by the radius to maximum winds, R.

Thus, with Equations (3) and (4), for the maximum significant wave height and the results in Figure 5, it would be possible to calculate the wave height at any location of interest and this may be a useful approach. Alternately, the wave height at any location of interest, H_*, can be approximated by the following:

$$H_* = H_{\max} \frac{U_*^2}{U_{\max}^2} \tag{6}$$

where U_* is the wind speed at the location of interest and $U_{\max}$ is the maximum wind speed in the hurricane wind field. The square relationship in Eq. (6) is consistent with the physics governing wave generation by wind, basically the Froude relationship.

Eq. (6) is applicable for deep water conditions. A method needs to be developed and incorporated to account for refraction, shoaling and wave damping that would occur across broad continental shelves. It is recommended that damping be based on a reasonable friction factor and the geometric characteristics of the shelf profile. It is likely that a set of curves and/or empirical equations could be developed to represent several characteristic shelf widths, etc.

Sheltered Waters

For purposes here, it is considered that the Storm Wave Characteristics efforts (Topics 1–5) and Wave Transformation efforts (Topics 7–10) will provide a basis for developing wave spectra outside the breaking zone for sheltered waters.

Interim Methodology Common to the Pacific Coast and Sheltered Waters and Gulf and Atlantic Coasts Landward of Breaking

Two interim methods will be described. Method 1 is more of a parameterized method based on as much proven engineering methodology as is available. Method 2 would apply advanced numerical Boussinesq wave models that have found applicability in the surf and swash (runup) regions. Because of the present uncertainty regarding the applicability of these more physics-based models to FEMA issues, the first phase of the interim method effort would be an evaluation of these models to establish whether or not they are capable of providing suitable estimates of static and dynamic wave setup for applications of interest here.

Method 1: Based on Proven Engineering Methodology

Static Wave Setup Component

The components of the interim methodology that are common to all coastlines commence at a nearshore reference depth outside the breaking zone. As noted previously, the nearshore wave information will be a product of the Wave Transformation effort. At this stage, it appears that the directional wave spectra provided at the nearshore reference depth will be a result of linear superposition. Since infragravity (nonlinear) waves can be significant to wave setup, runup, and beach erosion, especially on the Pacific Coast, the possibility of adding these infragravity components to the linear spectrum will be explored. Following this, a realistic wave transformation model that accounts for the particular characteristics of the nearshore profile will be applied to represent the wave characteristics as the waves propagate toward shore and through the surf zone. The S_{xx} term and other momentum flux terms will be calculated and the wave setup equation (Eq. (1)) integrated to determine $\bar{\eta}$ according to the particular setting. It is likely that a "WHAFIS-like" computer program will be developed to carry out calculations from the seaward location of nearshore data wave storage (again, directional spectra, a product of the Wave Transformation effort) to wave setup and runup.

Dynamic Wave Setup Component

Two rather direct procedures have been established to account for the dynamic wave setup. The method of Lo (1981) is to augment the static setup, $\bar{\eta}$, associated with the significant wave height by 50% (with possibly a reduction factor to account for two-dimensional effects).

A second approach to the dynamic wave setup would be to utilize the expression of Goda (1985)

$$\eta_{rms} = \frac{0.01 H_o}{\sqrt{\frac{H_o}{L_o}\left(1+\frac{h}{H_o}\right)}} \tag{7}$$

where h is the water depth at any location in the surf zone. The methods of Lo and Goda have been compared for one case and have been shown to yield reasonably similar results. Thus, either (or both) of these two approaches would appear to be appropriate for an interim methodology.

A third possible approach (discussed in more detail in Method 2 below) to predicting dynamic wave setup would be to utilize one of the more physics-based wave models (such as a Boussinesq model) that can represent both the static and dynamic components of wave setup and runup. Through exercising the model for a range of conditions, it could be possible to develop guidelines for the dynamic (and/or static) component of wave setup. This approach could facilitate exploration of the effect of wave "groupiness" on wave setup. Informal observations support that setup is dependent on the time series of breaking waves, including the grouping of larger waves. Therefore, very groupy wave trains may have relatively low static setups but large dynamic setups. Model runs using measured wave time series with different groupiness levels may yield results that could be used to develop a simplified procedure for Pacific Coast, large swell conditions.

Method 2: Based on Advanced Numerical Models

Advanced numerical models have been developed over the last several decades and have found applicability in the surf and runup zones (Madsen, et al., 1997a, 1997b; Sorensen, et al., 1998; Kennedy, et al., 2000). With specification of a directional spectrum seaward of the breaking zone as input, these models can calculate both the static and dynamic setup and runup; however, to the best of our knowledge, these models have not been applied or evaluated for purposes of addressing issues within the purview of FEMA's responsibilities. Therefore, the first phase of the interim methodology will be the evaluation of the applicability of these advanced models to provide suitable predictions of static and dynamic wave setup. This will be based on comparisons of predictions with measurements. If this method is successful, a separate wave breaking wave model would not be required.

Beach Profile Representation

Regardless of which of the two methodologies is selected for development of an interim methodology, beach profiles will be required. Under a flooding scenario, the profiles of interest will include those contours that are normally above water. which, for purposes here will be assumed to be reasonably well known. As noted, most of the wave setup results for which beach profiles are taken into account are for the case of uniform beach slopes. However, beach profiles in nature tend to be concave upwards and may include bar features. In some areas of application, reasonably good information describing beach profiles will be available whereas in others there may be only limited data. In the absence of any quality beach profile data, it is suggested that some nearshore profiles be surveyed and correlated with Equilibrium Beach Profile (EBP) theory (e.g., Dean and Dalrymple, 2000) to determine whether EBP theory is adequate for wave setup calculations.

EBP theory considers the beach profile to be described by

$$h(y) = Ay^{2/3} \tag{8}$$

in which h is the stillwater depth under normal conditions (say, relative to NGVD) at a seaward distance, y, from the normal shoreline and A is a dimensional parameter (units of length$^{1/3}$ termed a "Profile Scale Parameter") which depends on sediment size. The profile predicted by Eq. (8) is concave upwards and is monotonic. The value of A for most Florida profiles is on the order of 0.1 m$^{1/3}$ (0.15 ft$^{1/3}$), a value that corresponds to a mean sediment size of approximately 0.2 mm.

To summarize, there are several approaches by which beach profile information can be developed for a particular application.

Wave Breaking Model

As noted, improved models will be required to provide a realistic basis for wave breaking which governs the transfer of wave related momentum to the water column. Candidate wave breaking models include those by Goda, 1985; Guza and Thornton, 1981; Battjes and Jannsen, 1978;

Svendsen, 1984; and Dally, Dean and Dalrymple, 1985. An advantage of the latter model (termed the D^3 model) is that the same quantity (wave energy) that governs the wave momentum flux is modeled directly. Also, this model predicts, in accordance with observations, that initially breaking waves propagating over a horizontal bottom will approach an equilibrium wave height after which they will become stable (non-breaking). This feature has advantages for profiles in which a longshore bar and landward bar system is present.

In summary of this issue, the manner in which waves break and thus momentum transferred is important to obtaining the correct wave setup. Several models are available which predict much more realistic wave breaking than the commonly applied model in which the wave height is assumed proportional to the local total water depth.

Nonlinear Effects on S_{xx} at Breaking

Breaking waves tend to be quite nonlinear at breaking with peaked crest regions and broad flat troughs. Associated with this nonlinear feature is a momentum flux (S_{xx}) which is considerably smaller than that predicted by linear breaking waves. Figure 7 presents, for periodic waves, the ratio of nonlinear to linear S_{xx} at breaking versus relative water depth, h/L_o.

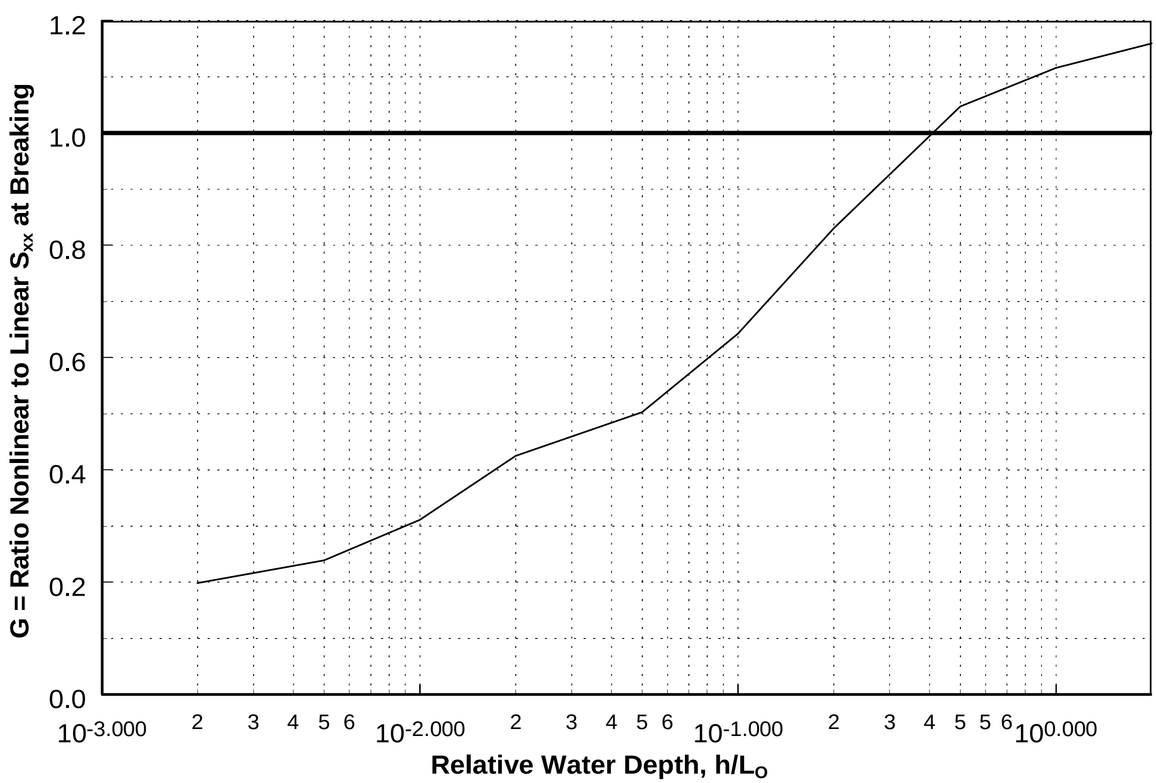


Figure 7. Relationship of nonlinear to linear S_{xx} at breaking versus relative water depth, h/l_o. based on stream function wave theory.

These results are based on stream function wave theory; however, other valid nonlinear theories exist. Clearly the magnitude of this effect justifies accounting for these nonlinearities in the quantification of S_{xx}.

In summary of the nonlinear S_{xx} issue, the effects of nonlinearities warrant their inclusion in a design methodology and several wave theories exist which can provide realistic results for the modification of S_{xx} at breaking.

Table 1 at the end of this report contains a summary of the key findings and recommendations for Topic 46. Table 2 at the end of this report presents estimates of times required to accomplish the various tasks in this topic.

3 AVAILABLE TOPICS

As noted in the Introduction, initially the Wave Setup topics included one “Available Topic”– “Topic 49: Review WRUP, available equation based program for wave run-up”. This topic was reassigned to the Runup and Overtopping Focused Study.

4 IMPORTANT TOPICS

There were two “Important” Topics in the wave setup category: (1) Topic 47: Develop Ideal Method Coupled With Storm Surge and Waves to Develop Setup, and (2) Topic 48: Develop Procedures for Dynamic Wave Setup. Each of these is discussed below.

4.1 TOPIC 47: DEVELOP IDEAL METHOD COUPLED WITH STORM SURGE AND WAVES TO DEVELOP SETUP

4.1.1 General

The so-called “Ideal Method” will be one in which the wave setup calculations are integrated into the storm surge model, requiring that the storm surge model also include the capability to compute or access wind fields and calculate the spatial and temporal distributions of waves. This so-called integrated model would include “wetting and drying” capabilities available in many advanced models and would have the capability to calculate realistic values of bottom friction coefficients. The model will also represent three dimensional features such as inlets, flows over barrier islands, and the gradients of the storm surge field due to the limited lateral dimension of the hurricane.

Some of these features are now represented in available storm surge models. The previously discussed nonlinear effects on S_{xx} could be represented by a subroutine that runs a nonlinear model such as a Boussinesq (see earlier references) or other model to evaluate S_{xx} (and potentially the other momentum flux terms) at breaking for the particular wave conditions. A practical difficulty in the direct application of the momentum flux contributions in long wave models is that the nearshore grid would need to be extremely small in order to resolve the breaker zone because the setup is a function of the gradients of radiation stresses, which could require grid resolution on the order of 10 m. An alternate approach would be to have look up tables based on the stream function or other nonlinear wave theory providing information similar to that presented in Figure 7. In this approach, wave setup could be computed external to the hydrodynamic model and either added linearly to the stillwater elevation or ideally included as a stress gradient in the hydrodynamic forcing. The first option would not require detailed nearshore resolution; however, the second option probably would.

Several groups are now actively pursuing the addition of a wave setup capability to the long wave model ADCIRC. These groups include the U. S. Army Engineer Research and Development Center (ERDC), (formerly the Waterways Experiment Station) and the National Oceanographic Partnership Program (NOPP). If one or both of these efforts are successful, it is possible that little additional work will be required for a portion of this topic. However, realistically, the models established for other than FEMA's applications probably will require further development for FEMA's specific purposes. Reasons include the need to retain as much of the governing physics as possible in the models and to ensure that the models are robust and can be applied over a wide range of physical settings by non-model specialists while still providing reasonably correct results. Thus, it is probably both realistic and prudent to consider the requirement of a considerable amount of development and testing over a wide range of conditions relevant to FEMA's responsibilities. The latter would naturally lead to the development of a User's Manual that would include results and guidance for a wide range of coastal settings (Figure 4).

Table 1 at the end of this report contains a summary of the key findings and recommendations for Topic 47. Table 2 at the end of this report presents estimates of times required to accomplish the various tasks in this topic.

4.2 TOPIC 48: DEVELOP PROCEDURES FOR DYNAMIC WAVE SETUP

4.2.1 General

The dynamic component of wave setup is a result of groups of waves that cause a variable setup/setdown in the offshore region and the further wave setup generation in the surf zone. Wave groups are more prominent for narrow energy spectra in the frequency domain with a narrow directional spread. According to some of the analytical and numerical models that have been developed to investigate wave setup oscillations induced in the surf zone, it appears possible that a type of resonance may occur further enhancing the dynamic wave setup. The so-called "sneaker waves" may be the result of two energetic spectral components propagating in almost precisely the same wave direction. A slight difference in wave direction causes a significant "detuning" away from resonance to the propagating forced wave.

In view of the above, a rational approach to the calculation of the dynamic component of wave setup would require a detailed description of the incident wave spectrum, including the directional and nonlinear wave characteristics. Recognizing the uncertain paths available for this topic and questions regarding the most appropriate pathway, a two-stage effort is proposed: 1) The first stage would be exploratory and would establish whether a rational approach or one or more ad hoc approaches is most suitable. The decision of whether or not a rational approach is feasible will depend on the prognosis for the required models being available within the next few years, and 2) A second phase to pursue the approach identified in the first phase. Each of these phases is discussed below and the overall effort is depicted in the flow chart below (Figure 8).

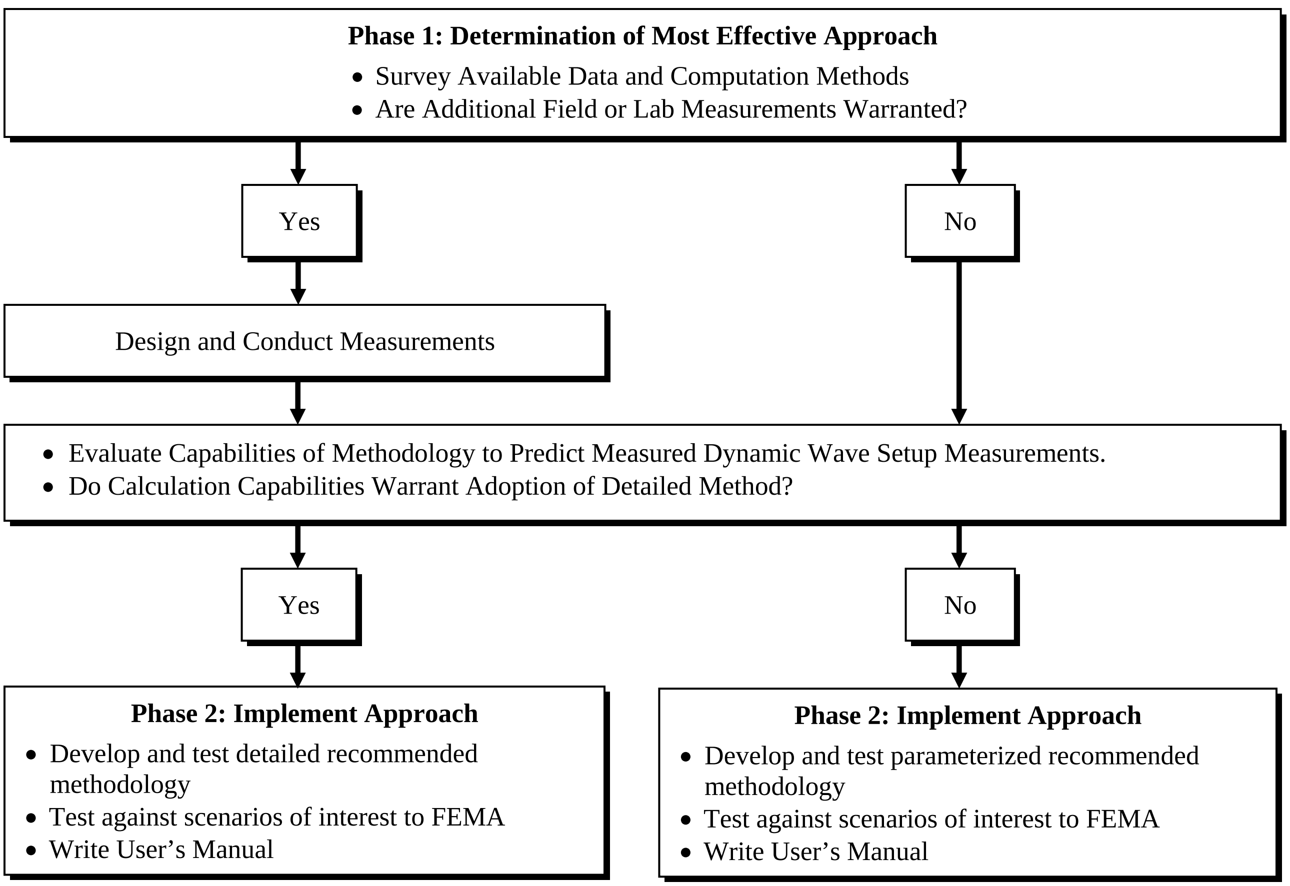


Figure 8. Flow Chart: Process of determining methodology for dynamic wave setup.

4.2.2 Phase 1. Determination of Most Effective Approach for Representing Dynamic Wave Setup

This phase of the task would be exploratory and would include establishment of existing documentation and development and comparison with calculation procedures. Each of these is discussed below.

The literature and available data relating to dynamic wave setup would be reviewed to identify data for further examination and methodologies for calculating wave setup. Argus camera systems (Holman and others) have been installed in a number of locations in the world and contain dynamic wave setup and dynamic wave runup information. Also, the field studies by Guza and Thornton (1981) that were carried out with a runup wire parallel to and a few centimeters above the beach surface contain dynamic setup information if the raw data are still available. Selection of data for further examination should include a preference for field situations in which quality offshore wave data are available. Efforts should be made to locate international sources of quality dynamic wave setup data. For example, Goda (1975) has published guidance for calculating dynamic wave setup and may have valuable data sets. The studies of Nielsen and colleagues, while not conducted for the purpose of measuring dynamic wave setup (the dynamic component was purposely averaged from the data), contain a lower limit of dynamic setup that may be useful for checking. Several authors (Schaffer and Svendsen, 1988; Schaffer and Jonsson, 1990; Symonds, Huntley and Bowen, 1982; and others) have presented methodologies for calculating long period waves in the surf zone resulting from wave groupiness. Additional laboratory and/or field experiments designed to address FEMA's responsibilities may be warranted and recommended. Additionally, as discussed earlier, the detailed Boussinesq wave models (see earlier references) that have been developed during the last few decades may be suitable for predicting wave setup and wave runup.

The second phase of the effort is to assess the available data and the capabilities of the existing computational methodologies to be evaluated by comparing predictions with available data and to decide on a procedure for proceeding toward an adopted methodology. The review here identified only two existing readily applied approaches for predicting dynamic wave setup (Goda, 1985; Lo, 1982). Advantages of developing a methodology based on detailed representations of the forcing spectrum will be based on the availability and/or prognosis of the development of such information.

4.2.3 Develop Selected Approach for Application

At this stage of the effort, it is considered that a decision will have been made to adopt either a detailed methodology or a parameterized approach for calculating dynamic wave setup. Subsequent efforts will include development and testing the recommended methodology against scenarios of interest to FEMA's flooding responsibilities and the writing of a User's Manual.

Table 1 at the end of this report contains a summary of the key findings and recommendations for Topic 48. Table 2 at the end of this report presents estimates of times required to accomplish the various tasks in this topic.

5 ADDITIONAL OBSERVATIONS

Although the underlying physics of wave setup is well understood, current guidance relating to the calculation of wave setup for the wide range of settings within FEMA's area of responsibility (Figure 3) is lacking. With the emphasis on the nearshore region over the last three decades or so, the capability to improve current guidance is substantial.

Two general methods are considered, either of which would represent a significant advancement: 1) Use of available and proven engineering procedures, and 2) Use of advanced numerical wave models (ANWM), in particular the Boussinesq models. The first method is definitely possible and can be packaged to be applied by a Study Contractor (SC). A question exists as to whether the advanced wave models can be applied by a SC over a broad scale of settings and wave and nearshore geometries. Further, some of these ANWMs are proprietary, they are computationally intensive, advancing rapidly and undoubtedly their capabilities will be greater in a decade than at present. Finally, even if a decision is made to progress with an ANWM which would be run by a SC as a "black box", it would be desirable that the SC have a less computationally intensive procedure as a general check. On the other side, the potential (present?) capabilities of the ANWM are very attractive, being able to predict both wave setup and wave runup without concern if wave setup is included twice in wave runup.

Regardless of the method adopted, a significant effort will be completed in a search for high-quality wave setup data with an emphasis on field data. It is expected that some of the more valuable data will be based on carefully documented high water marks during extreme events which are conditions of special concern to FEMA.

6 SUMMARY

6.1 CATEGORY SUMMARY

The Wave Setup Focused Study Group on was tasked with identifying programs that would lead to state-of-the-art improved capabilities of Study Contractors to better accomplish FEMA's responsibilities in establishing hazard zones. These tasks were organized in six topics with one topic later transferred to the Wave Runup and Overtopping Focused Study Group. Of the five remaining topics, three were listed as "critical" and two were "important". All five were considered of concern to the Atlantic and Gulf coats, Pacific and Sheltered coasts. The alternatives above were discussed at Workshop 2 in Sacramento in February 2004, and recommendations developed based on the consensus of the Technical Working Group.

6.2 SUMMARY TABLES

Table 1. Summary of Findings and Recommendations for Wave Setup

Topic Number	Topic	Coastal Area	Priority Class	Availability/ Adequacy	Recommended Approach	Related Topics
44 & 45	Define, Document, Compile Data	AC	C	MAJ	The recommended approach for this topic is the same for all geographic regions: Conduct a thorough examination of all available relevant literature with an emphasis on quality field data sets. These would include experiments conducted especially to investigate wave setup and especially "experiments of opportunity" in major storms including high water marks. Organize data by "settings" identified in this report.	11
		GC	C	MAJ		
		PC	C	MAJ		
		SW	C	MAJ		
46	Interim Method	AC	C	MAJ	Several possibilities exist. The "Interim Method" should include consideration of the following: (1) static and dynamic setup, (2) irregular waves (implicit in (1) above). (3) characterization of nearshore bathymetry, (4) a valid wave breaking model, (5) nonlinearities in S_{xx}, and (6) wave damping where appropriate. An attempt should be made to ensure that the interim method address as many of the settings identified as possible	1, 6, 9
		GC	C	MAJ		
		PC	C	MAJ		
		SW	C	MAJ		
47	Develop Ideal Method - Coupled	AC	I	PRODAT	The recommended approach for this topic is the same for all geographic regions. The ideal method would be one in which the storm surge model also incorporates a wave generation model. The wave generation model would predict directional spectra so that the characteristics of the dynamic setup could be calculated directly. It is recommended that this topic be approached as a two phase effort with the first phase evaluating approaches and the second phase pursuing the approach identified.	9, 10, and many beyond those identified in Table 1
		GC	I	PRODAT		
		PC	I	PRODAT		
		SW	I	PRODAT		
48	Dynamic Wave Setup	AC	I	PRODAT	This topic could be incorporated into Topic 47, but a more realistic approach is to parallel Topic 47 with a first phase to evaluate existing methodologies that could	9, 10, and many beyond
		GC	I	PRODAT		
		PC	I	PRODAT		

Table 1. Summary of Findings and Recommendations for Wave Setup						
Topic Number	Topic	Coastal Area	Priority Class	Availability/ Adequacy	Recommended Approach	Related Topics
		SW	I	PRODAT	be applied. The results of the first phase would guide the second phase, which would implement the optimal approach identified. It is anticipated that the actual procedures developed would be somewhere between a full physics-based approach which would proceed from a directional spectrum, and the approaches available from Lo and Goda which are either based on somewhat simple calculations or empirical. A probable approach would be one in which the dynamic wave setup is based on parameterized spectra determined as a function of wind fields and continental shelf width of interest.	those identified in Table 1

Key:
Coastal Area
AC = Atlantic Coast; GC = Gulf Coast; PC = Pacific Coast; SW = Sheltered Waters
Priority Class
C = critical; A = available; I = important; H = helpful
Availability/Adequacy
"Critical" Items: MIN = needed revisions are relatively minor; MAJ = needed revisions are major
"Available" Items: Y = availability confirmed; N = data or methods are not readily available
"Important" Items: PRO = procedures or methods must be developed; DAT = new data are required;
PRODAT = both new procedures and data are required

Table 2. Time Estimates for Wave Setup Topics		
Topic Number	Topic	Time (person months)
44	**Better Define and Document; Summarize What to Consider and How to Approach; Data Requirements**	
	Improve Definitions in Guidelines	1
	Develop Approach Strategy	2
	Write Report	2
	Incorporate Feedback, Finalize	2
	TOTAL	7
45	**Compile Example/Data Sets to Perform Tests**	
	Compile Data Sets From US Literature	2
	Visit US Investigators to Obtain Data Sets as Necessary	3
	Visit International Investigators to Obtain Data Sets as Necessary	3
	Compile Data Sets Into Useful Data Base	3
	TOTAL	11

Table 2. Time Estimates for Wave Setup Topics

Topic Number	Topic	Time (person months)
46	**Develop Interim Method (look at CEM as a fall back, or University of Hawaii SPM Procedure)**	
	1. Select Engineering Based or Boussinesq Model Method	4
	2. Develop Recommendations for Nearshore Profiles	2
	3. Evaluate and Make Recommendations for Wave Breaking Model (Not Required if Boussinesq Model Selected)	3
	4. Develop Recommendations for Representing Nonlinear Wave Effects on S_{xx} at Breaking Model (Not Required if Boussinesq Model Selected)	2
	5. Evaluate Candidate Methods for Dynamic Wave Setup and Develop Recommendation Model (Not Required if Boussinesq Model Selected)	2
	6. Test Model Over a Wide Range of Settings Consistent With FEMA's Responsibilities	2
	7. Evaluate Whether Existing Methods Include Wave Setup Effects Implicitly and if so, Account for These	2
	8. Develop Report (User's Manual) Describing Recommended Interim Methodology	2
	TOTAL	10–19
47	**Develop Ideal Method Coupled With Storm Surge and Waves to Develop Setup**	
	Evaluate Various Available Models, Select Model for Further Development	4
	Further Develop Model for FEMA Applications	12
	Incorporate Nonlinear Effects on S_{xx} (Reduced effort if Boussinesq Model Selected)	2
	Ensure That Recommended Methodology Does Not Include Wave Setup Effects Implicitly Model (Reduced effort if Boussinesq Model Selected)	3
	Test Model Over a Wide Range of Settings Consistent With FEMA's Responsibilities	4
	Develop Report (User's Manual) Describing Recommended Model	4
	TOTAL	24–29
48	**Develop Procedures for Dynamic Wave Setup**	
	Evaluate Various Available Models, Select Model for Further Development	4
	Further Develop Model for FEMA Applications	8
	Exercise Model for Scenarios and Settings of FEMA Interest	4
	Test Model Over a Wide Range of Settings Consistent With FEMA's Responsibilities	4
	Develop Report (User's Manual) Describing Recommended Model	4
	TOTAL	24

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